

Derivation of contemporary vertical deformation associated with the Cascadia Subduction Zone from historical leveling surveys

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Annual Project Summary

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Introduction

The Cascadia subduction zone has been hypothesized as a location for a large megathrust earthquake by many researchers. Geodetic, GPS, and strain data provide evidence for active crustal strain buildup throughout the region. Based on models of crustal deformation, the potential for a $M > 9$ event has been suggested. Additional seismic hazards are potentially large earthquakes occurring on crustal faults within the Seattle Fault zone and large intraplate earthquakes within the subducting Juan de Fuca plate (e.g. Nisqually earthquake, February 28, 2001, $M_{6.8}$). The Cascadia subduction zone is formed by the oblique convergence of the Juan de Fuca and North American plates (Figure 1.). It is generally accepted that a potential megathrust earthquake would be the result of slip on

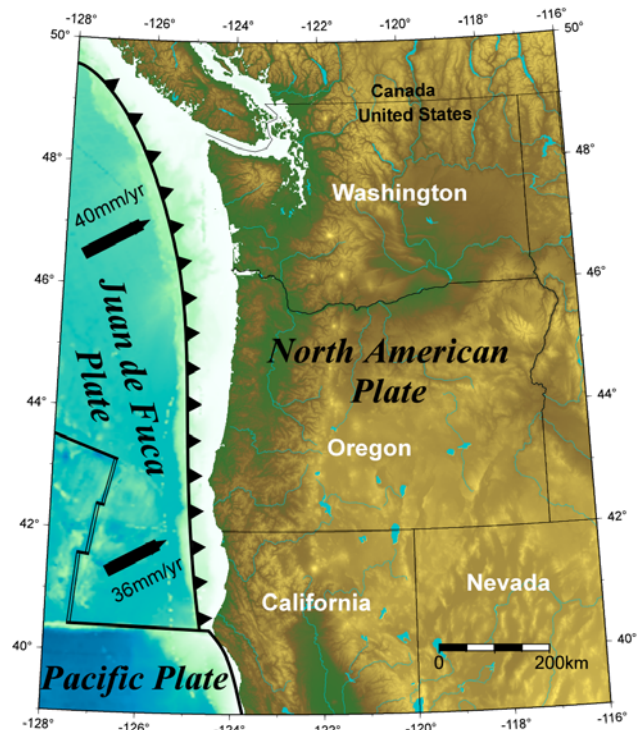


Figure 1 – Tectonic map of the Cascadia Subduction Zone

a locked portion of the subduction interface, although the size and location of the seismogenic zone is unclear. Most models of the Cascadia subduction process are constrained by horizontal crustal strain and displacement data. Vertical deformation data were used as the major constraint in very few studies.

Vertical deformation is not included as a constraint in many models because of the lack of an up-to-date, comprehensive analysis of the available leveling data, the poor vertical resolution of GPS, and the lack of tilt measurements in the region. Prior to a major releveing in the late 1980s, Reilinger and Adams (1982) presented evidence for landward tilting of the Oregon and Washington coast. Holdahl et al. (1989) analyzed leveling data in northwest Washington and southwest Canada and Mitchell et al. (1994) re-analyzed some of the leveling data after the 1980s surveys but limited their study to coastal areas.

A better understanding of the vertical deformation throughout Cascadia will help constrain the size and location of coupling along the plate boundary and eventually help us better assess the earthquake potential in the region. In this study, I analyze historical leveling data for Washington, Oregon, and northern California to produce a more comprehensive map of uplift rates of the region.

Table 1. Data Summary

Pairs of leveling lines	200
Data points from leveling	5149
Data points from tide gauges	16
Minimum time between releveing	3 years
Minimum number of points per line	10
Minimum leveling line length	10 km
Order of leveling lines	1, 2

Data Description

Crustal uplift rates were calculated from repeated leveling. I calculated uplift rates by taking the difference between elevations at common benchmarks then dividing by the time between surveys (Table 1, Figure 2). I also calculated an estimated error for each uplift rate based on the elevation error estimates and the error in time between surveys. The calculated rates for each pair of leveling lines are referenced to some unknown datum. I identified and removed outliers using a least square B-spline and median absolute deviation technique (Figure 3). The uplift rates were then adjusted to a common datum by a weighted least squares procedure. Each data point was assigned an initial weight proportional to the inverse of the square of the estimated error. The adjustment was performed and residuals were calculated. A bivariate cosine series was used as the basis function for the adjustments.

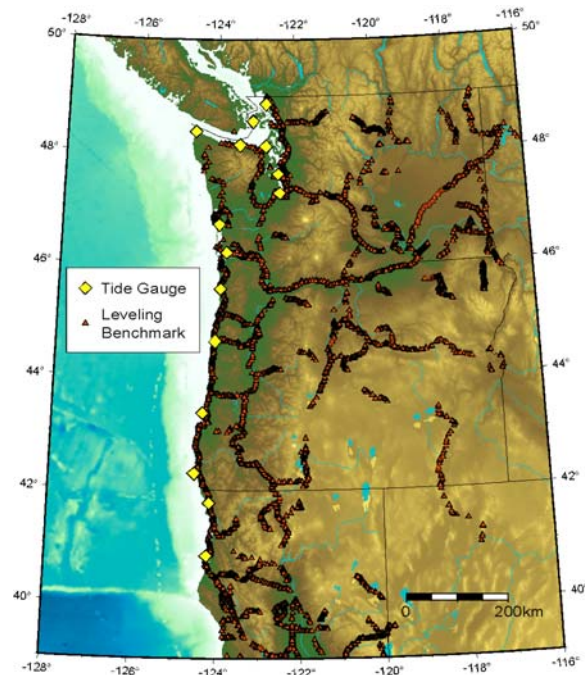


Figure 2 – Map of leveling benchmarks and tide gauges used in this study.

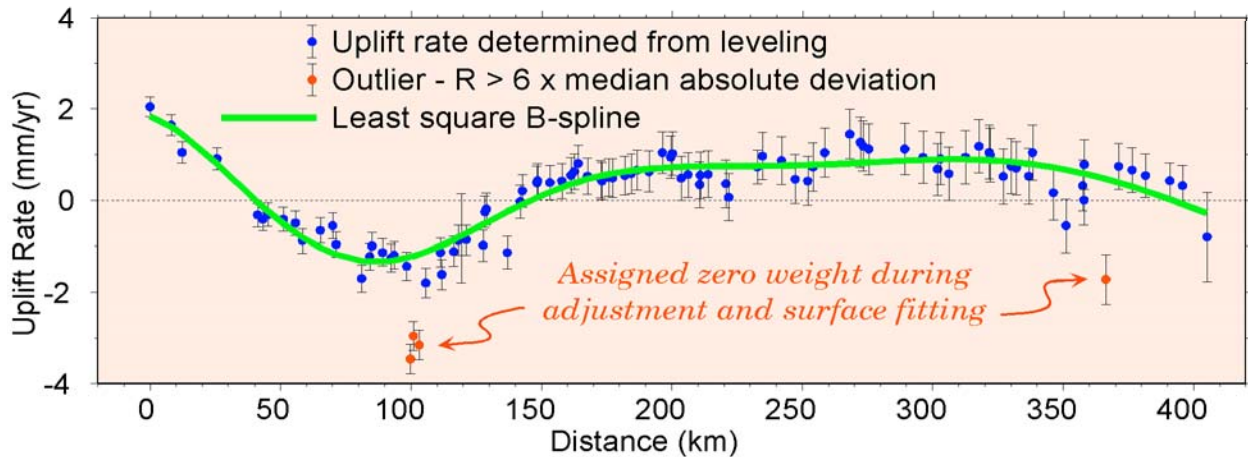


Figure 3 – Example of outlier detection using the median absolute deviation method.

In order to use sea level as the datum, I obtained uplift rates calculated from tide gauges from Ray Weldon at the University of Oregon. These uplift rates were given slightly higher weight and held fixed during the adjustment.

Smoothing and Gridding

Once outliers were identified and the data were adjusted to a common datum, I smoothed the data using a robust, weighted, moving average technique. I assigned initial weights based on the estimated data error and the distance of the data point from the node. After investigating the trade-off between smoothness and RMS residual, I chose a node spacing of 10km and a search radius of 50km. After the initial weighted average was calculated, I rescaled the weights based on the residual and the median absolute deviation. The process was repeated until no significant improvement was made in the RMS residual.

Results

The uplift rate map shown in Figure 4. was produced by fitting a minimum curvature surface to the smoothed data. I used the GMT surface (Wessel and Smith, 1991) routine for the surface

fitting. The image is illuminated based on the relative weighted data density. That is, the bright and dark areas represent the highest and lowest data density, respectively. The uplift rates

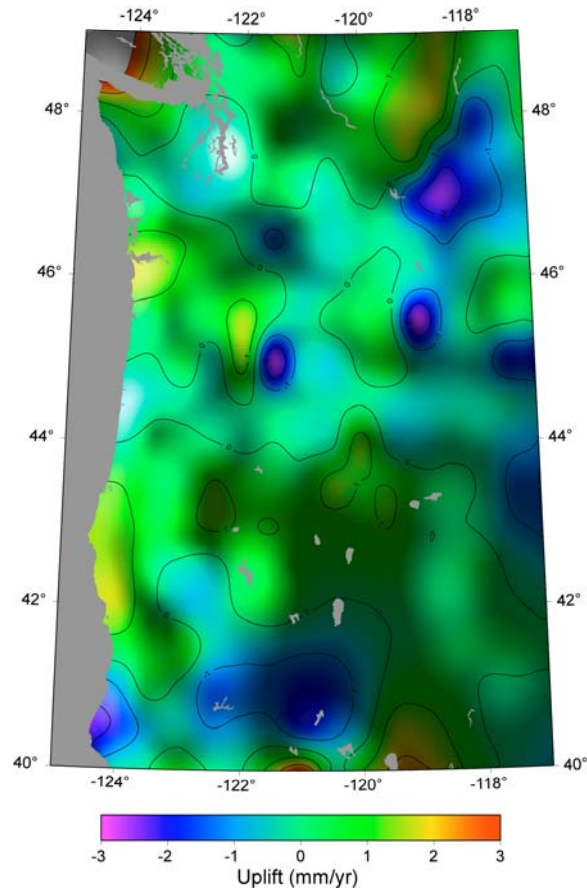


Figure 4 -Uplift rate map. Contours are in mm/yr and the illumination is based on the relative data density shown in Figure 5.

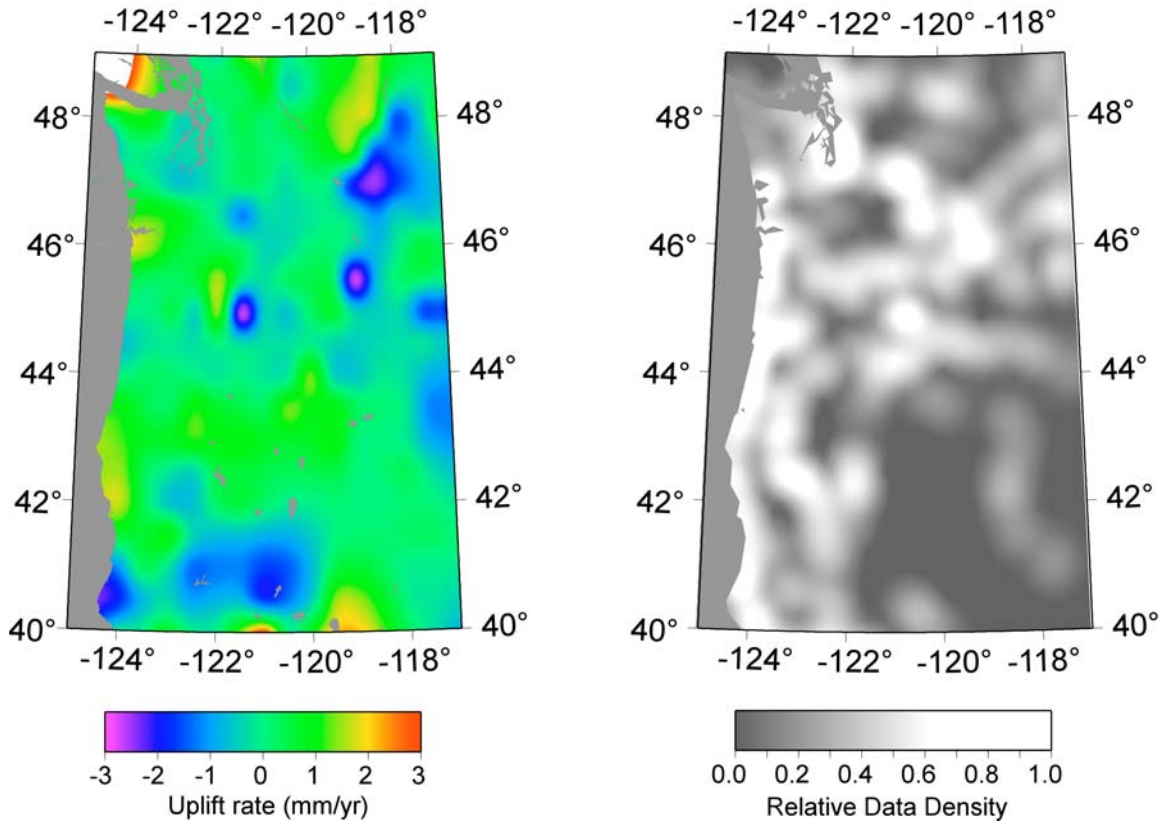


Figure 5 – Uplift rate and relative data density maps. These maps are combined to produce the map in Figure 4.

and relative data density are shown individually in Figure 5. Cross sections through the model and data are shown in Figures 6 and 7.

Discussion

Cross sections A., B., and C. shown in Figure 6 are nearly north-south profiles of uplift rates throughout Cascadia. The profiles indicate several regions of uplift along the coast. In several regions the coastal uplift continues inland and can be better seen in east west cross sections. Cross-sections of uplift rates are plotted at six east-west locations (Figure 7, Sections D.-I.). The three northern cross sections (Figure 7 Sections D., E., and F.) and the two southernmost (Figure 7 Sections H. and I.) indicate landward tilting near the

coast. The rate of landward tilting appears to vary significantly along the coast with the fastest deformation occurring to the north (Figure 6 and 7). The east-west cross section through central Oregon at 45°N (Figure 7 Section G.) shows relatively little vertical deformation anywhere along its length. In an earlier study I suggest that the subduction zone deformation is segmented (Verdonck, 1995). The lack of vertical deformation across central Oregon may represent a transition in subduction behavior between the northern segments (Figure 7 Sections D., E., and F.) and southern (Figure 7 Sections H. and I.). The north-south variation in subduction behavior is also evident in the north-south cross sections (Figure 6 Sections A., B., and C.). The variation in deformation along the

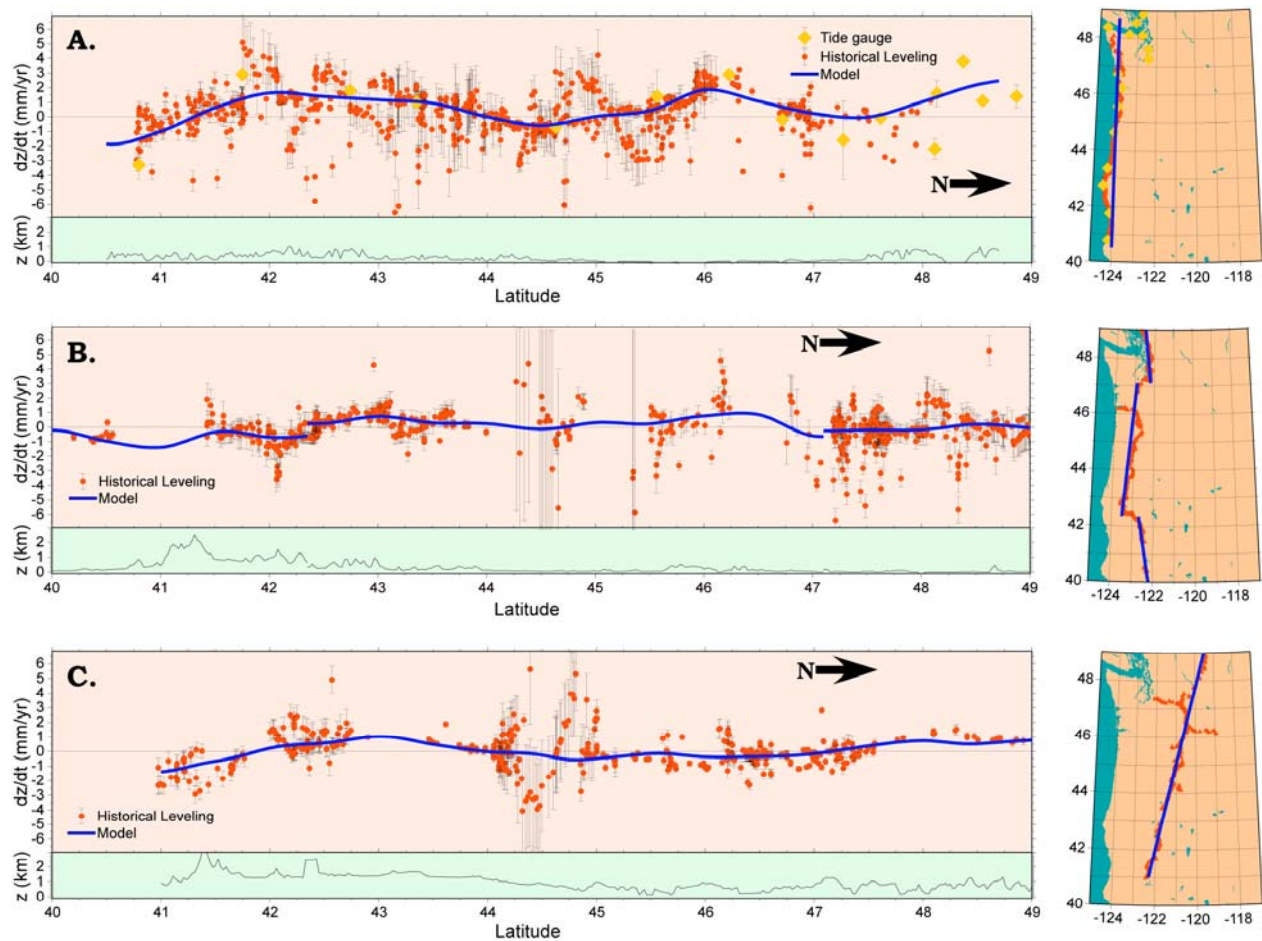


Figure 6 – Uplift rate cross sections running nearly north-south. The small maps to the right of each cross section indicate the locations.

subduction zone may be due to a variety of phenomena including, but not limited to, variable coupling across the plate interface, crustal structure variation, or slab dip angle.

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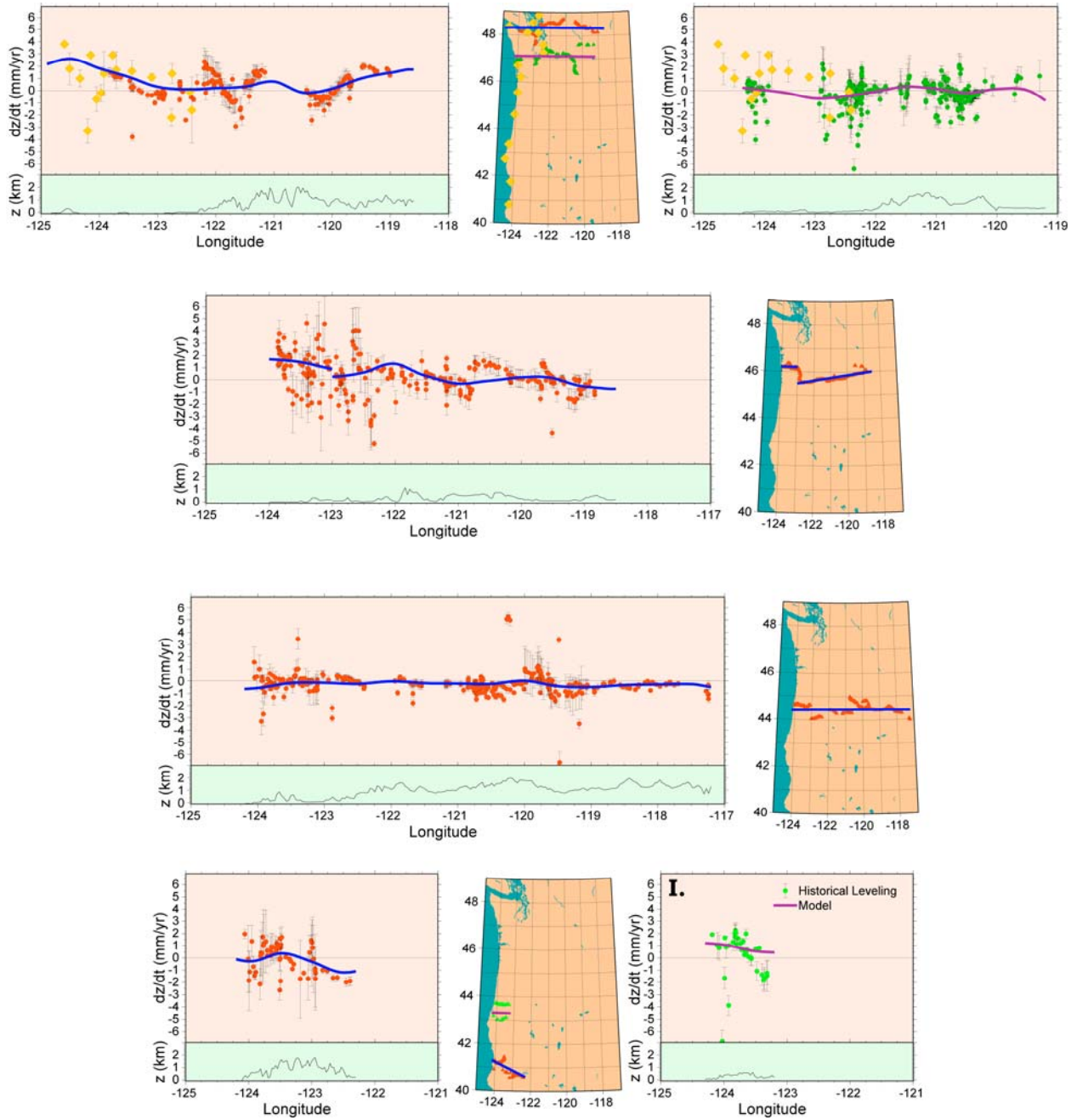


Figure 7 – Uplift rate cross sections running nearly east-west. The small maps to the right of each cross section indicate the locations.

Non-technical summary

A better understanding of the vertical crustal deformation throughout the Pacific Northwest of the United States eventually help us better assess the earthquake potential in the region. In this study, I examine historical leveling data from Cascadia and calculate uplift rates throughout the region.

Vertical deformation rates are calculated from historical differential leveling. I calculate rates by taking the difference between elevations at common benchmarks and dividing by the time between surveys. The uplift rates are adjusted using a least squares procedure. Uplift rates calculated from tide gauges were included in the adjustment and held fixed, thereby making sea-level a common datum.

The results indicate landward tilting in several regions along the coast alternating with regions of little or no deformation. There were no regions with seaward tilting. In some regions the coastal uplift continues inland but landward tilting appears to dominate the deformation. The rate of landward tilting varies significantly along the coast with the fastest deformation occurring to the north. At about 45°N, there is little vertical deformation either at the coast or inland. The lack of vertical deformation across central Oregon may represent a transition in subduction behavior between northern and southern segments.

Presentations and Abstracts

Verdonck, D., 2004, *Uplift and subsidence along the Cascadia subduction zone determined from historical repeated leveling*, Trans. AGU, Fall Meet., Abstract Submitted.

Verdonck, D., 2004, *Vertical crustal deformation in cascadia from historical leveling*, GSA Abstracts with Programs, Paper 67-12.

Verdonck, D., 2004, *Determination of Vertical Surface Deformation From Repeated Historical Leveling in Cascadia*, Eos. Trans. AGU, Spring Meet., Abstract S421-04.

Verdonck, D., 2004, *An overview of ongoing analysis of active vertical deformation in Cascadia*, Annual PANGA Investigators Meeting and Workshop, Victoria, BC, Canada, February 2004.